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**SUBMILLIMETER RESEARCH: A PROPAGATION
BIBLIOGRAPHY**

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report is an annotated bibliography given on the subject of submilli- meter propagation. Several articles are recommended as a good starting point for reviewing the current state-of-the-art.		

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SUBMILLIMETER RESEARCH: A PROPAGATION BIBLIOGRAPHY

This annotated bibliography was prepared to provide an introduction to the field of submillimeter propagation. Several articles are recommended for those just beginning to review the field; these articles are marked by a * in the listing. To aid in visualizing the behavior of atmospheric propagation in the submillimeter wave region of the spectrum, three figures are included in this bibliography. Figure 1 shows the attenuation due to absorption in decibels/kilometer as a function of wavelength (from reference 119). Figure 2 shows a theoretical estimate of scattering losses at these wavelengths (from reference 33). Figure 3 shows experimental data superimposed on the theoretical absorption curve.

The list of references in this bibliography is not meant to be exhaustive but it will provide the user with an easy entry into the field.

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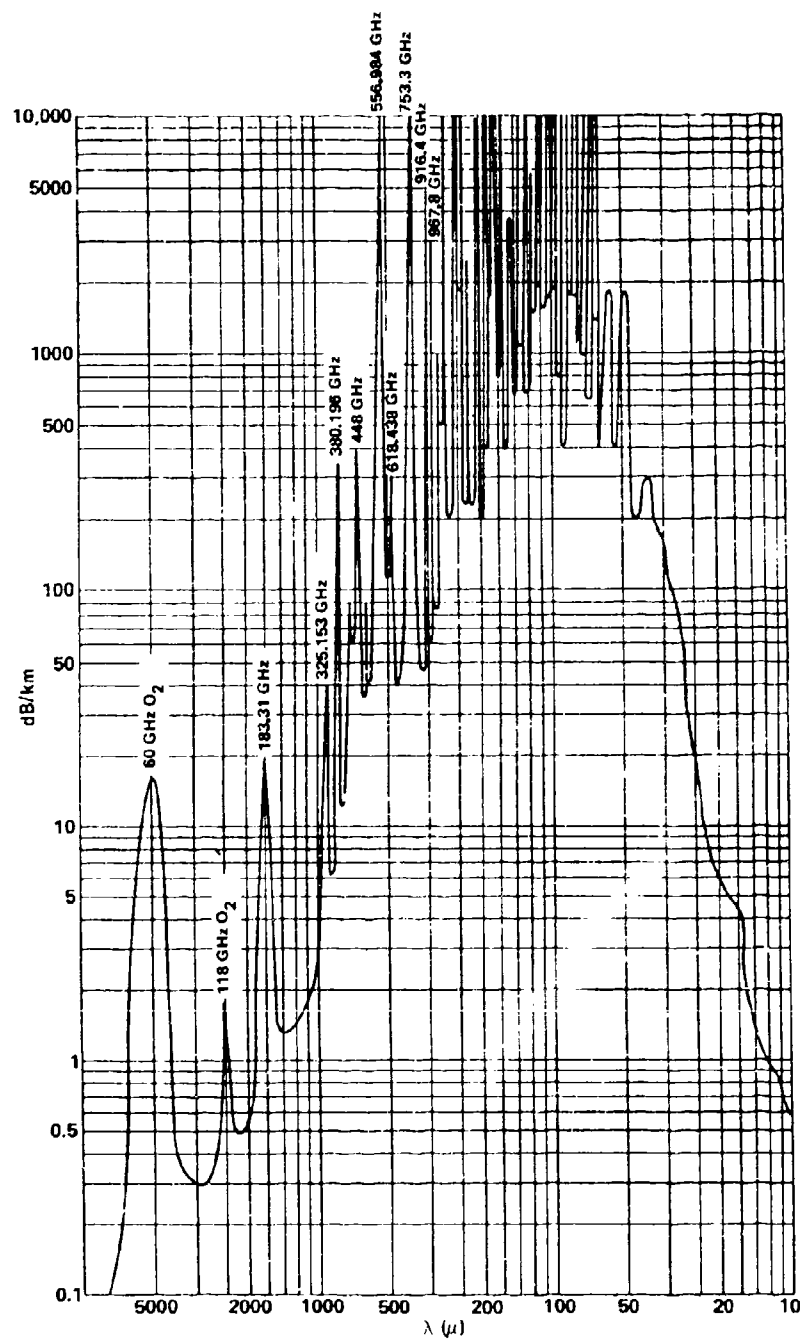


Figure 1. Absorption from 10 to 5000 μ at 1-atm pressure, 293°K, and absolute humidity $\rho = 7.5 \text{ gm/m}^3$ - Shape: Zhevakin-Naumov.

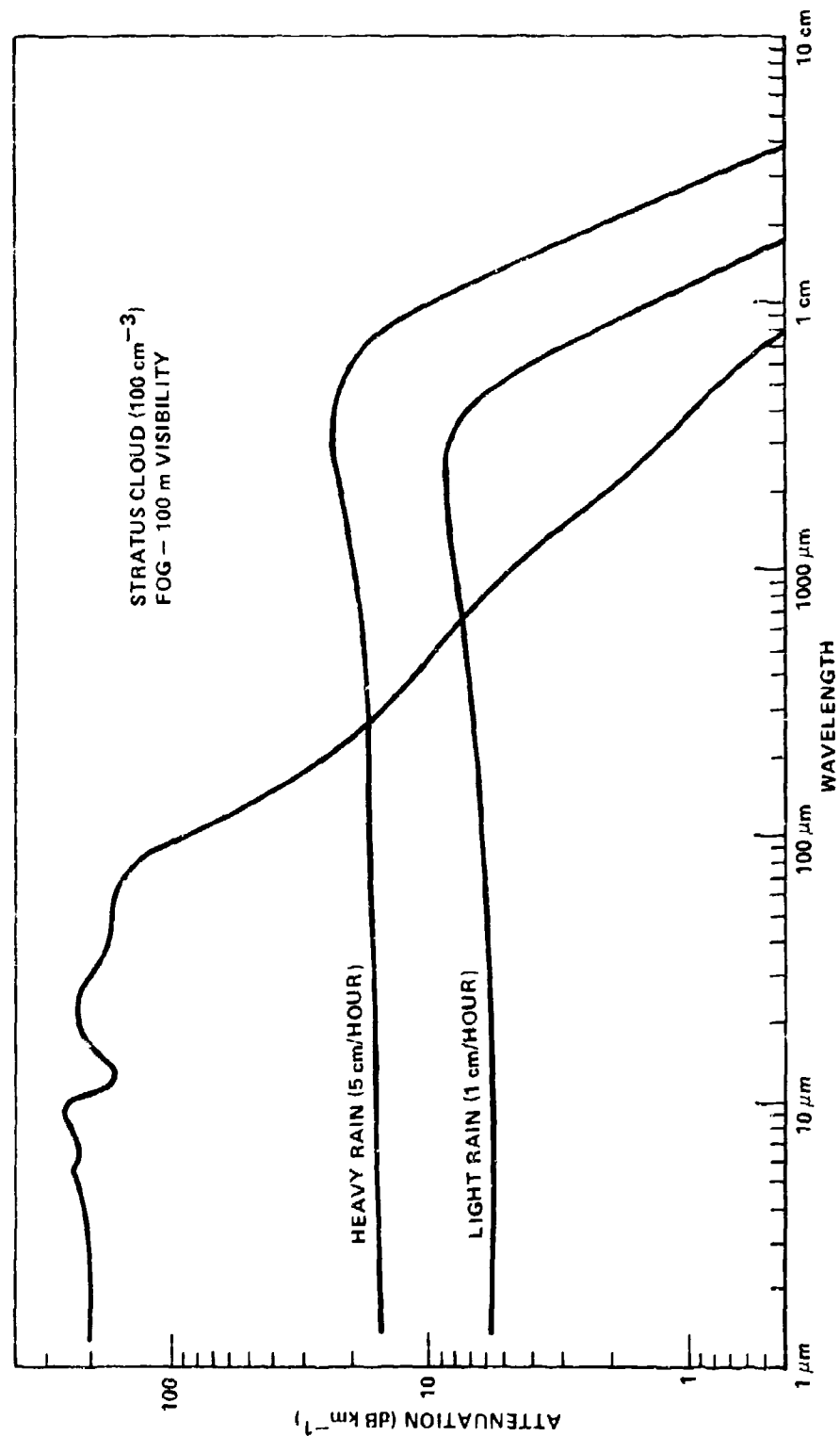


Figure 2. Cloud scattering losses.

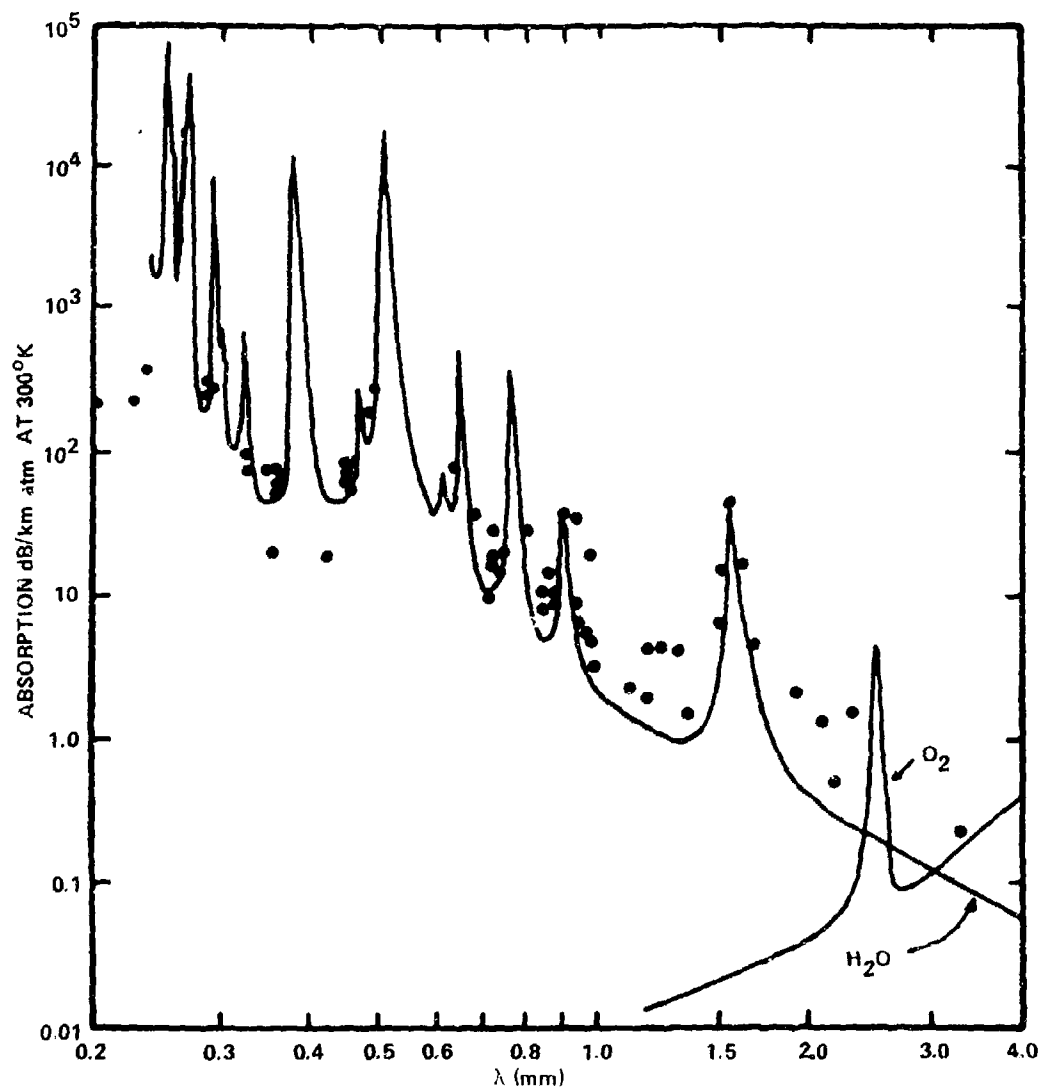


Figure 3. Comparison of theoretical and experimental atmospheric absorption between 0.2 and 4.0 mm.* (The solid curve labeled H_2O is the theoretical curve for water vapor; experimental points are indicated).

*J. A. Bastin, *Infra. Phys.*, Volume 6, 1966, p. 209, with addition experimental points.

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Absorption coefficients for water vapor are calculated for constant pressure and temperature range of 173°K to 373°K. Temperature dependence can be modeled by T^{-n} where $3.2 < n < 4$ in the transmission windows.

2. Agabekyan, K. A., Zrazhevskiy, A. Yu., Kolosov, M. A., and Sokolov, A. V., "Study of the Absorption Dependence Upon the Air Pressure at the Wave Length of 0.29; 0.36 and 0.45 mm," Radio Eng. and Elect. Phys., Volume 16, No. 9, 1971, pp. 1433-1437.

An echelette grating spectrometer with a mercury arc for a source and an InSb detector used to measure absorption over a path length from 25 to 125 m. Almost quadratic pressure dependence found. For 7.5 gm³, 760 mm Hg and 20°C:

<u>Wavelength</u>	<u>Absorption</u>
0.29 mm	236 dB/km
0.36 mm	63 dB/km
0.45 mm	67 dB/km

3. Agabekyan, K. A., Zrazhevskiy, A. Yu., Kolosov, M. A., and Sokolov, A. V., Procedure and Results of Measurements of Absorption Coefficients of Submillimeter Radiation in Atmospheric Water Vapors, Proc. 9th All-Union Conference on Radiowave Propagation, Part II, June 1969, p. 126.
4. Aganbekyan, K. A., Zrazhevskiy, A. Yu., Sokolov, A. V., and Stroganov, L. I., "An Investigation of the Width and Shape of the $\lambda = 0.92$ mm Spectral Line of Pure Water Vapor," Radio Eng. and Elect. Phys., Volume 20, 1975, pp. 21-28.
5. Apletalin, V. N., Meriakri, V. V., and Chigryay, Y. Y., "Measurement of the Absorbing and Reflecting Properties of Water at Wavelengths from 2 to 0.8 mm," Radio Eng. Elect. Phys., Volume 15, 1970, pp. 1286-1288.

Measured dielectric constant of water. At wavelengths less than 1.6 mm, the dielectric constant of water differs from the Debye behavior.

6. Armand, N. A., Izyumov, A. O., and Sokolov, A. V., "Fluctuations of Submillimeter Radiowaves in Turbulent Atmosphere," Radio Eng. and Elect. Phys., Volume 16; No. 8 1971, pp. 1259-1266.

Theory developed for propagation of a plane monochromatic sub-millimeter wave in the surface layer of a turbulent atmosphere. Experiment carried out in the wavelength range of 0.88 to 0.99 mm. Theory and experiment show qualitative agreement on the fact that the intensity of the fluctuation decreases with an increase in absorption. Experiment shows a larger effect than theory predicts.

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In Spanish, a review.

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Measurement of attenuation in snowfall up to 2 mm/hour over a 680-m path. The attenuation in snow is 30% to 40% larger than the attenuation in rainfall of the same rate. Between 0.4 and 1.8 mm/hour the attenuation (dB/km) is given by $0.7 + 2.3I$, where I is the snowfall rate.

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Attenuation of rain in summer thunderstorms. Used backward wave oscillator (BWO) and an InSb detector. Between rainfall rates of 0 to 12 mm/hour the attenuation at 0.96 mm is 2.5 to 3 dB larger than the attenuation at 8.6 mm. The attenuation (dB/km) can be approximated by $1.53I^{0.638}$, where I is the intensity of rain in mm/hour.

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Description of equipment to be used in propagation measurements in the wavelength range of 0.83 to 1.2 mm.

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Calculations of atmospheric absorption in the range of 0.25 to 4.0 mm. Compared results to experiments. Contains a brief review of experiments conducted before 1966.

14. Bastin, J. A., Gear, A. E., Jones, G. O., Smith, H. G. T., and Wright, P. J., Spectroscopy at Extreme Infra-red Wavelengths: III Astrophysical and Atmospheric Measurements, Proc. Roy. Soc. London A278, 1964, pp. 543-573.

Measurement of attenuation of solar radiation by clouds at 1.2 ± 0.4 mm. Used an objective diffraction grating on a telescope.

15. Birch, J. R., Burroughs, W. J., and Emery, R. J., "Observation of Atmospheric Absorption Using Submillimeter Maser Sources," Infrared Physics, Volume 9, 1969, pp. 75-83.

Used laser sources at 337, 311, 195, 190 and 118 μm to measure absorption of the atmosphere and of pure water vapor. The attenuation obtained at 293°K was as follows:

Wavelength (μm)	Attenuation (dB/km/g/m ³)
337	7.89
311	46.3
195	86.2
190	118.7
118	114.3

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Fourier transform spectrometer and white cell used to obtain line positions and attenuation in the atmospheric windows in the wavelength range from 1.0 to 0.1 mm. Comparison is made to theory.

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Measurements made in laboratory of atmospheric attenuation from 500 to 1500 GHz.

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- 19.* Burch, D. E., "Absorption of Infrared Radiant Energy by CO₂ and H₂O III. Absorption by H₂O between 0.5 and 36 cm⁻¹ (278 μm - 2 cm)," J. Opt. Soc. Am., Volume 58, 1968, pp. 1383-1394.

Fourier transform spectrometer used to obtain absorption data over 121-to 469-m path length. Samples were pure H₂O or H₂O + N₂ or air.

Total pressures were from 2.5 torr to 1 atm; temperature was 296°K. Source was a high pressure Hg-arc lamp; detector was a helium cooled, gallium doped, germanium bolometer.

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Measurements at 337 μm over horizontal path in a fog. Visibility measurements were used to deduce fog water content. Comparisons were made to measurements conducted in a controlled atmosphere.

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Complex refractive indices measured in the wavelength range from 100 to 500 μm over the temperature range of 5° to 70°C.

23. Chamberlain, J., Zafar, M. S., and Hasted, J. B., "Direct Measurement of Refraction Spectrum of Liquid Water at Submillimeter Wavelengths," Nature, Physical Science, Volume 243, 1973, pp. 116-117.

Reflectivity of water was measured at ambient temperature in the wavelength range of 100 to 500 μm .

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Used superheterodyne radiometer to measure attenuation of 34 dB/km/g/m^3 horizontal attenuation with respect to water vapor density. Used path lengths between 3 and 70 m.

25. Chen, C. C., Attenuation of Electromagnetic Radiation by Haze, Fog, Clouds and Rain, Rand Corporation Report R-1694-PR, April 1975, AD-A011 642.

Computation of all available attenuation coefficients due to aerosols as a function of wavelength. Very little data in the submillimeter range.

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Used same equipment described in Reference 24 and 26. Attenuation measured at 309 GHz was 3.35 dB/km and at 316 GHz was 5.55 dB/km per g/m^3 of water vapor density.

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Radiometric measurements of atmospheric absorption for frequencies above 100 GHz.

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- 33.* Deirmendjian, D., "Extinction of Submillimeter Waves by Clouds and Rain," The Rand Corporation, Working Note WN-8816-PR, August 1974.

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Emphasis on data below 100 GHz but extrapolation of data to 300 GHz is possible. Good review of meteorological data.

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Measurements in the wavelength range of 0.5 to 3.0 mm of atmospheric propagation. Theoretical calculations using kinetic line shape. Line center and line broadening measurements as well as atmospheric window measurements were made. A 6-m path length was used.

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Calculation of absorption and complex dielectric constant.

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Theoretical evaluation of correlation and the effects of absorption.

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Calculation of optical constants of water and ice from 2 to 200 μm .

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Continuation of the theme presented in Reference 66.

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Measurement at standard conditions (7.6 gm/m^3) and temperature of 18°C) gave 4.5 dB/km.

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Attenuation at standard conditions was found to be 16.3 dB/km. Used a BWO as a source.

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Used mercury arc for source, an echelette grating spectrometer, and a Golay cell for a detector. Measured absorption around the wavelengths 0.2, 0.29, 0.36, 0.45, 0.73 and 0.87 mm. At standard conditions:

Wavelength (mm)	Attenuation (dB/km)
0.2	334
0.29	336
0.36	66.7
0.45	73
0.73	23.2
0.87	17

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Measurement of absorption using Fourier transform spectrometer.

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Theoretical calculations at 4, 14, 28, and 41 km using Air Force atmospheric-absorption-line parameter data tape.

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112. Ulaby, F. T., "Absorption in the 220-GHz Atmospheric Window," IEEE Trans, AP-21, March 1973, pp. 266-269.
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-RB	1
-RC	1
-RD	1
-RE	1
-RE, Mr. Pittman	1
-RF	1
-RG	1
-RH	1
-RK	1
-RN	1
-RR, Dr. Hallows	1
Mr. Shapiro	1
Mrs. Davis	2
-RRE	50
-Y	1
-RBD	3
-RPR (Record Set)	1
(Reference Copy)	1